NUISANCE

NeUtrino Interaction Systematics ANalyser by Comparing Experiments
NeUtrino Interaction Synthesiser Aggregating Constraints from Experiments
NeUtrino Interaction Systematics from A-Neutrino sCattering Experiments
...

https://nuisance.hepforge.org/
P. Stowell et al 2017 JINST 12 P01016

Imperial College London
The University Of Sheffield.
Imperial College London
UNIVERSITÄT BERN

NuInt 2017
28 June, Fields Institute, Toronto

Clarence Wret, Patrick Stowell, Luke Pickering, Callum Wilkinson
Help from S. Dytman, U. Mosel, Hayato-san, J. Sobczyk, C. Juszczak, K. Mahn, K. McFarland, G. Perdue, S. Dolan, P. Lasorak, J. Calcutt, C, L. O'Sullivan, and more...

Disclaimer #1

Plots shown are snapshots of the generators in their current states

Disclaimer #2

I'm informing of a new tool, not here to present lovely new physics (sorry)

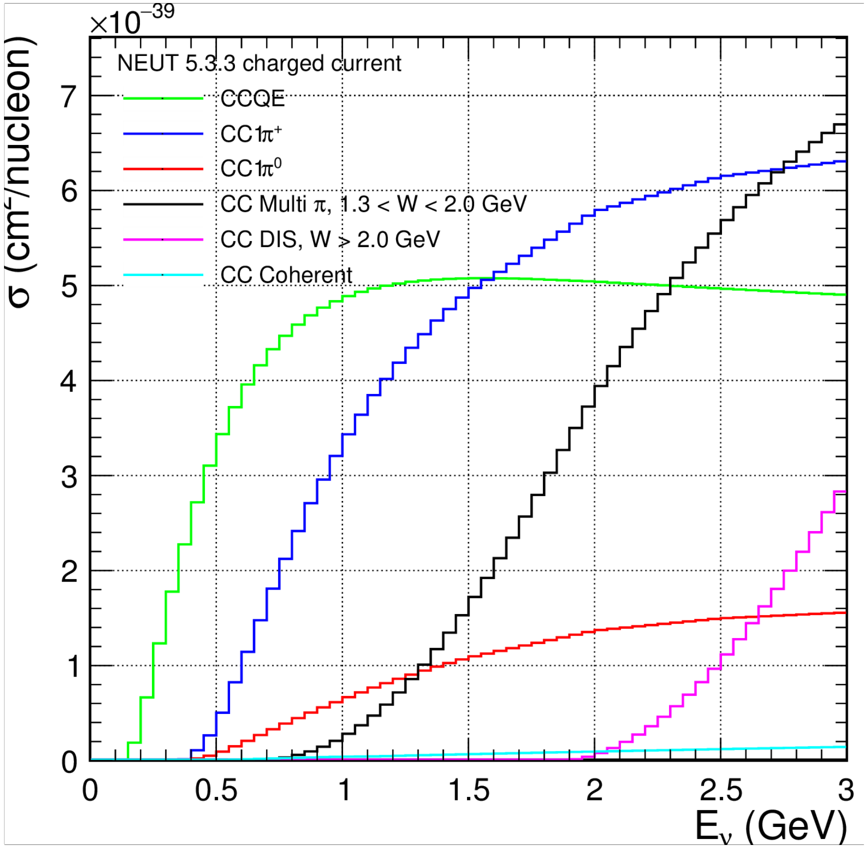
NUISANCE does not guarantee your physics makes sense!

Introduction

- Precision neutrino oscillation measurements require well modelled neutrino interaction: $E_\nu^{rec} \rightarrow E_\nu^{true}$ mapping

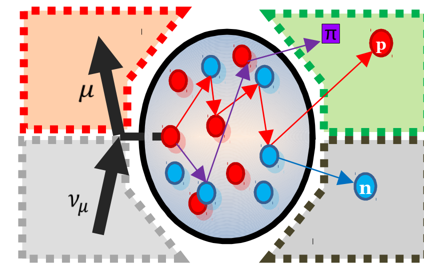
$$N_{SK} \sim \Phi_{SK}(E_\nu)\boxed{\sigma(E_\nu)}\epsilon_{SK} P(\nu_\alpha \rightarrow \nu_\beta)$$

- Well modelled cross-section at near detector with $E_\nu \sim 1$ GeV? But what about
  - Far detector with oscillated E_ν
  - Different acceptance at far detector
  - Possibly different target materials
- Calorimetric reconstruction requires accounting for neutral particles
  - Effect partially informed from cross-section simulations

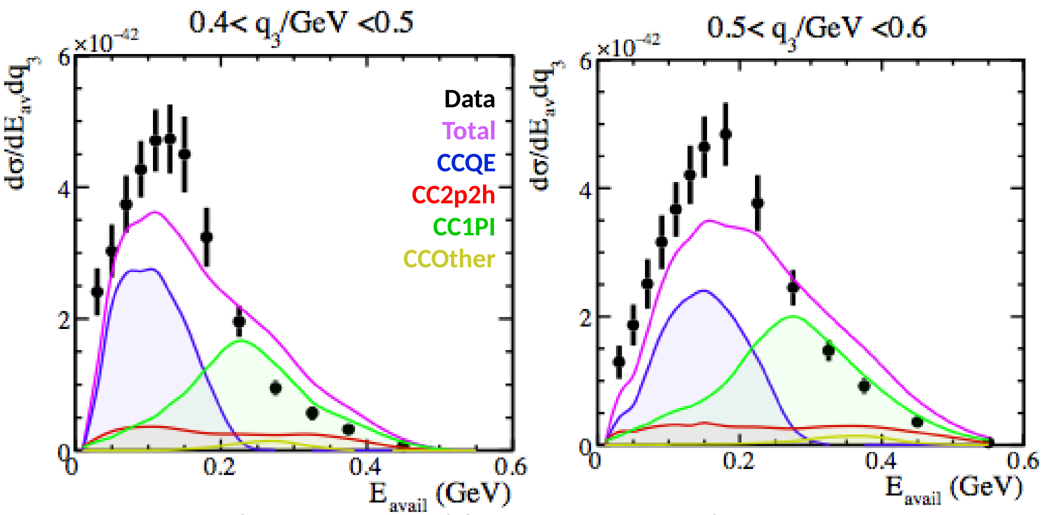


Introduction

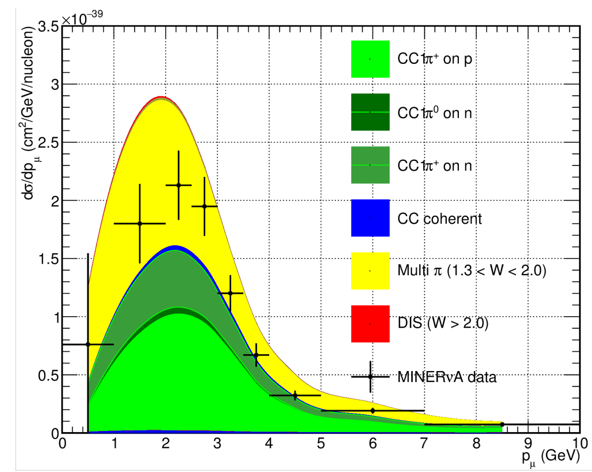
- In an experiment, event selection is done by topology
  - e.g. CC0π selection has contributions from 2p2h, SPP, FSI
- The experiment requires a "full theory" in the generators
  - e.g. how does sophisticated FSI model "play" with simple Rein-Sehgal SPP



- Difficult to assign Data/MC disagreement to a particular interaction model from only one data-set, especially if doing so "by-eye"



NEUT 5.3.6 and MINERvA CC-inc (Phys. Rev. D 93, 071101)

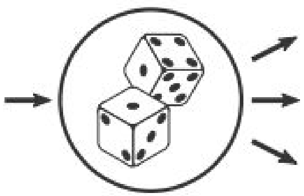


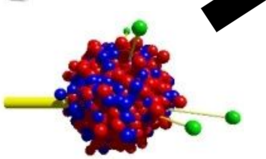
NEUT 5.3.6 and MINERvA CCNπ (Phys. Rev. Lett. 116)

- Identified a need for large custom Data/MC comparisons
  - Started with NEUT, grew to support GENIE, NuWro and GiBUU

How NUISANCE works

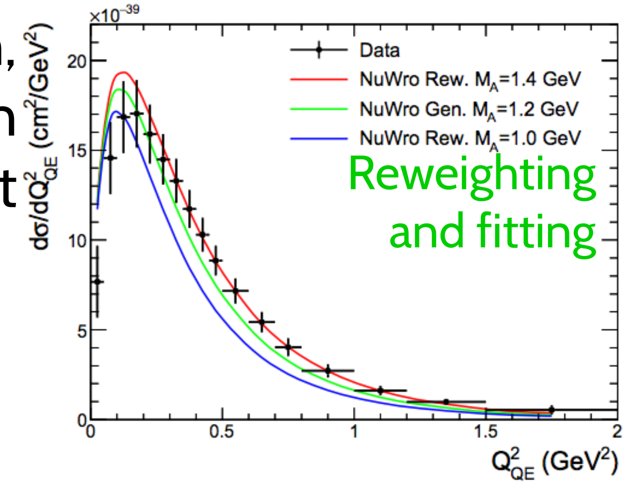
Generators provide particle vectors

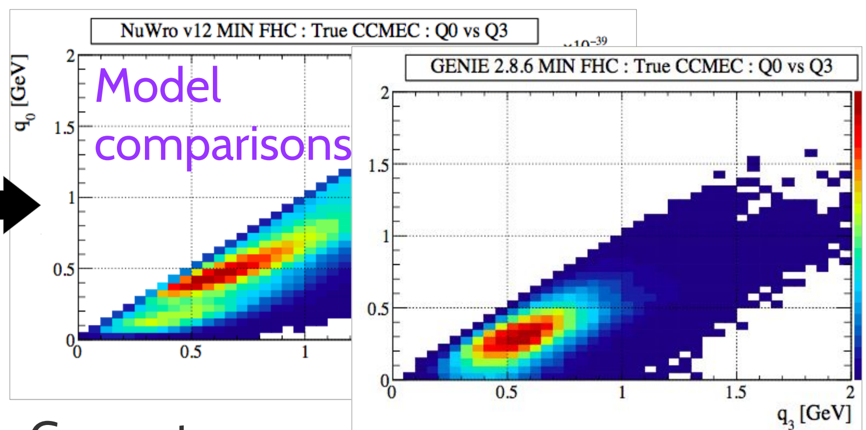




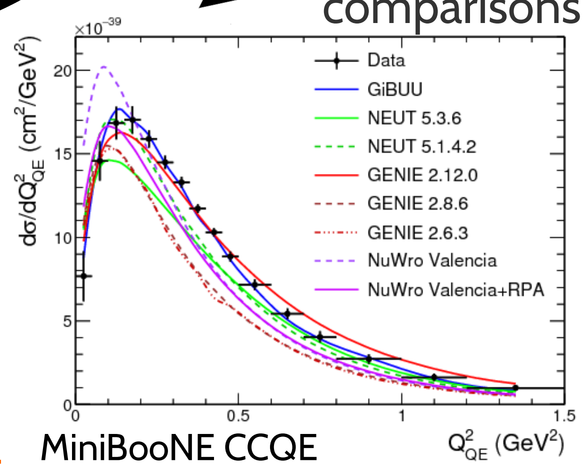
Convert into common event format

Event selection, cross-section scaling, reweight

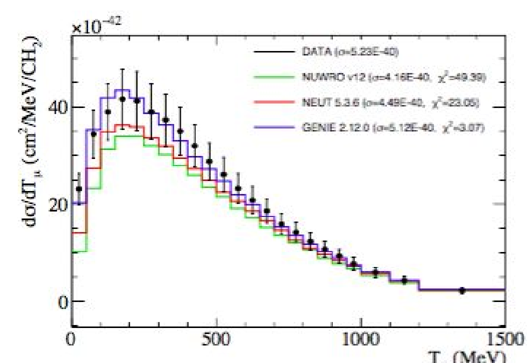




Generator comparisons



MiniBooNE CCQE



MiniBooNE CC1π^+

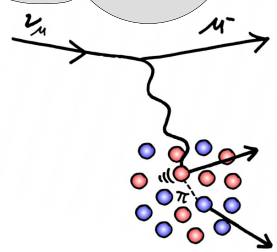
Imperial College London

Using NUISANCE

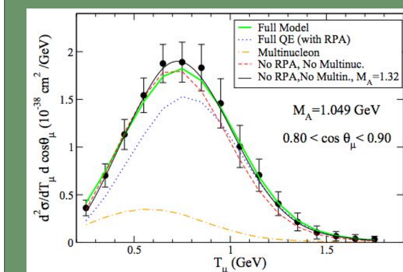
- >200 neutrino dataset for multi-generator comparisons, tunings and systematics studies
- Learn more and talk to us: hepforge, trac wiki, Slack channel, Github, mailing list
- MSc+early PhD student friendly
  - Model interpretation is the tricky bit, making the plots is easy!
- The data distributions are stand-alone from NUISANCE
  - Working with Durham IPPP (HEPdata) on extending their database
- Unsure on a signal definition for an experiment? We've got them
- Can't find the flux for an experiment? Read this long monologue
- Seen examples in Minoo, Marcela and Steve's talks, thanks!

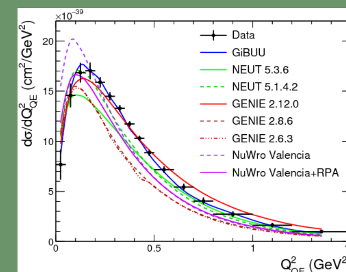
For theory/generator development

Theory model



Confront with cross-section data





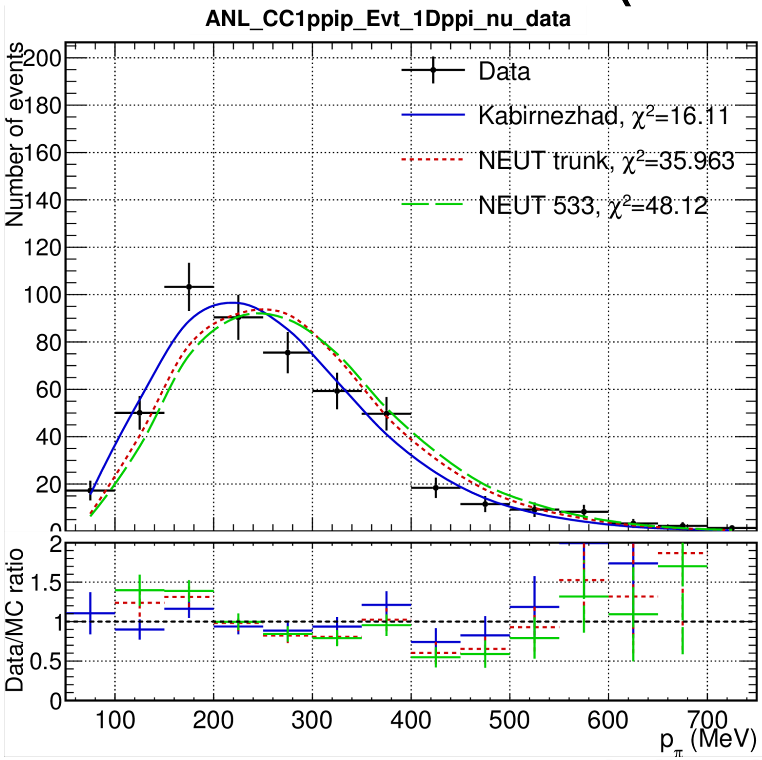
Implement in generators

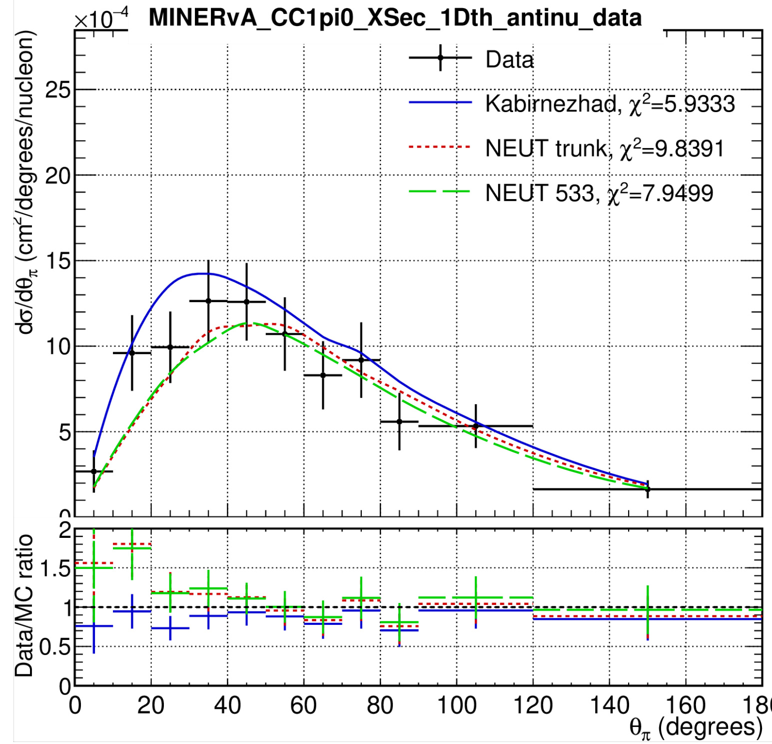
Improve future cross-section and oscillation measurements

- Once theory is implemented in generators, it **should** be easy to update predictions
- Confront the generator model(s) with as much data as possible
- Highlight when generator A might be getting it right → Implement alternative in generator B
- Parameter tuning also supported

Theory uses at T2K

- Minoo Kabirnezhad and I have been evaluating her SPP model implementation in NEUT (see more in her talk)





- Evaluating impact of model selection on external and T2K data, looking at its impact on oscillation analyses
- Parameter tuning to nucleon data (e.g. M_A^{RES}, M_A^{bckg}, $C^A_5(0)$)
- How does the SPP play with NEUT's initial state and FSI models

For cross-section analysers

Theory model

Confront with cross-section data

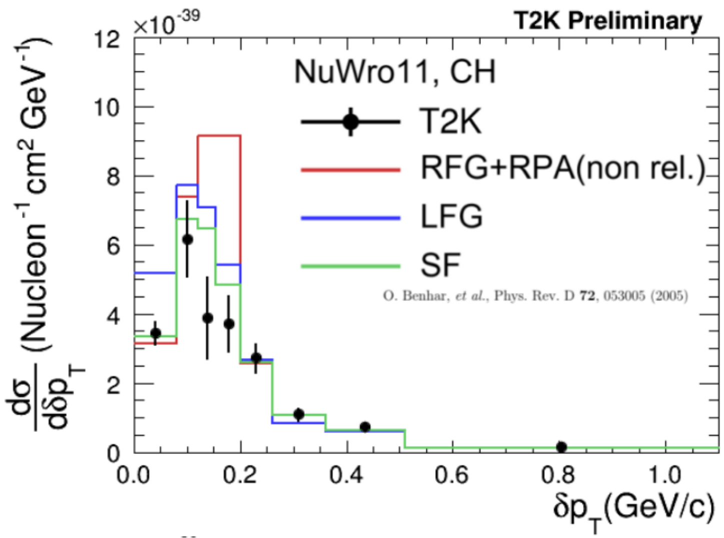
Implement in generators

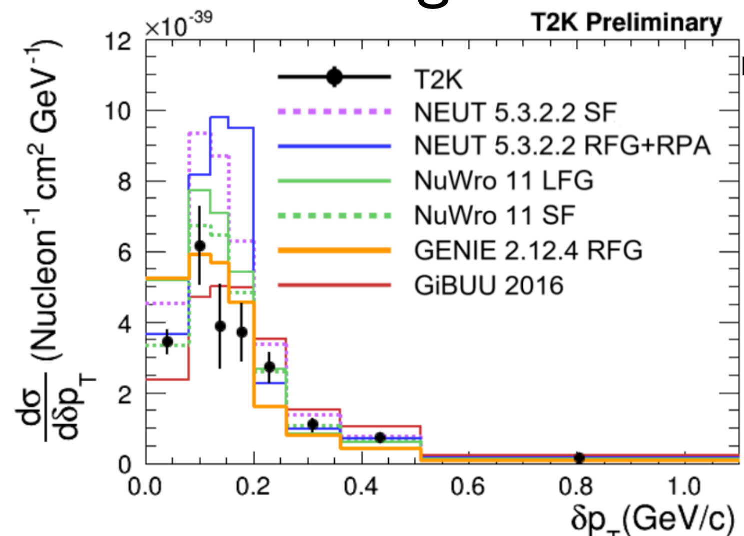
Improve future cross-section and oscillation measurements

- Cross-section analysers efficiency correct based on MC, also rely on MC for phase space corr.
  - Use multiple generators/models to eval.?
  - Get uncertainties from external data?
- What distributions are particularly interesting?
  - Where do the generators/models disagree?
  - Tensions? Sensitivity to effects in phase space?
- What do modern generators say about older cross-section measurements?
- Ensure your experiment's data release is robust by implementing it into NUISANCE

Cross-section uses at T2K

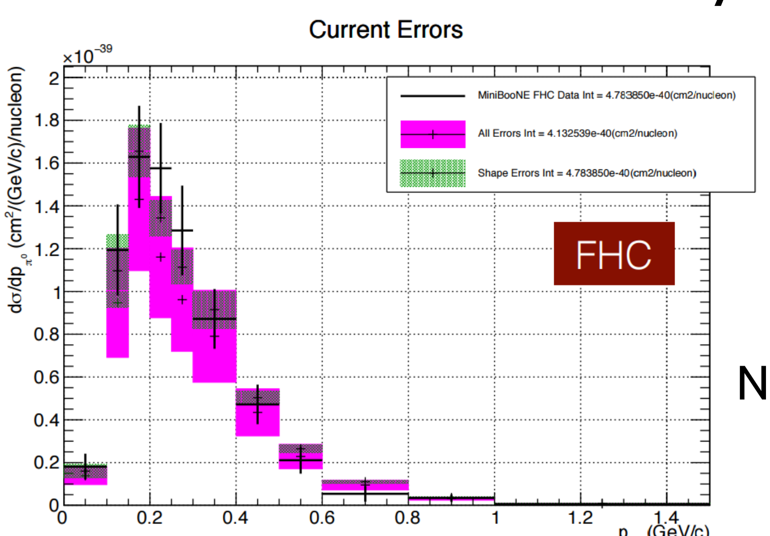
- Stephen Dolan CC0πNp (transverse variables) measurement looked at effect of various initial state models in NuWro and generators





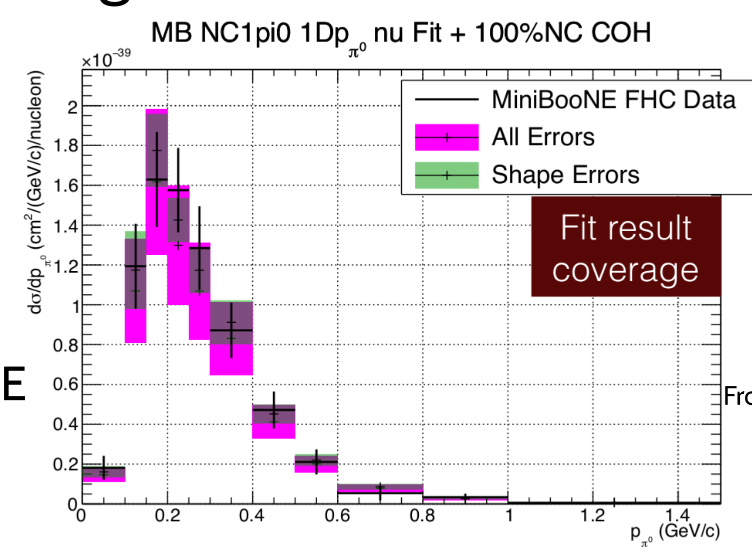
From S. Dolan

- Pierre Lasorak's NC1γ selection has large NC1π⁰ background: used MiniBooNE NC1π⁰ data to survey the coverage of the NEUT model



Fit with

NUISANCE



From P. Lasorak

Oscillation analysers

Theory model

Confront with cross-section data

Implement in generators

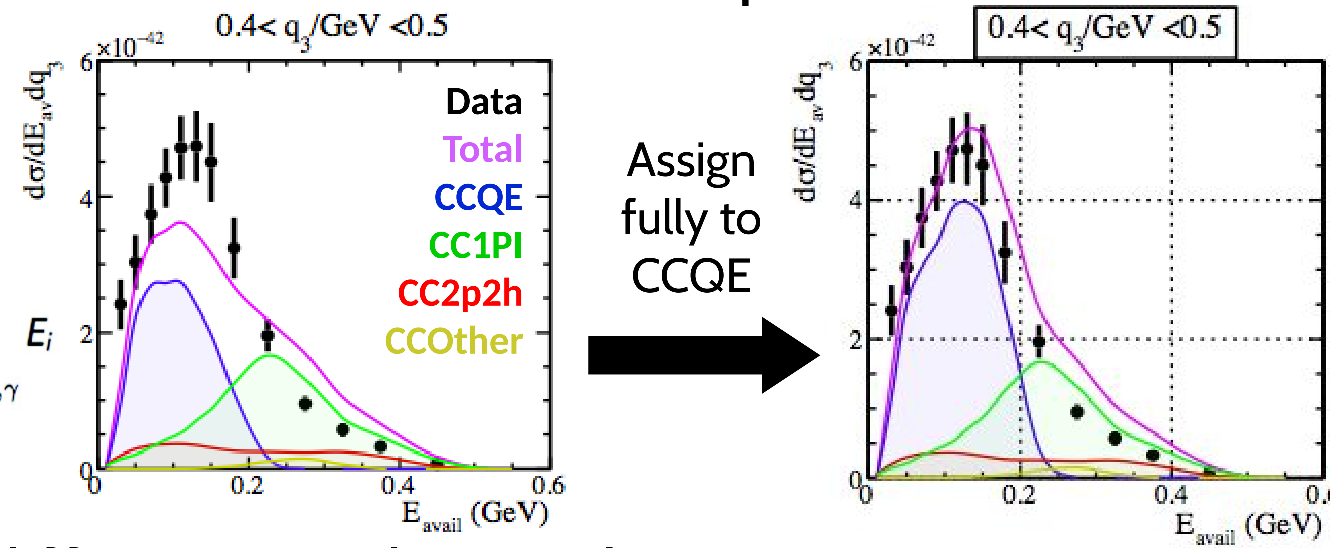
Improve future cross-section and oscillation measurements

- Select default models for making full experiment simulation
  - Based on external and/or internal data
- Estimate central values and uncertainties for cross-section parameters using a wealth of data
- Effective parameterisations inspired by various data-MC discrepancies
  - e.g. assigning 2p2h-sensitive data-MC difference to a weight applied to 2p2h events

NUISANCE uses at T2K

- Can use to construct fake-data studies
- MINERvA CC-inclusive data indicates the NEUT prediction is missing ingredients in mid-E_{avail} (see Rik Gran's talk)
- Is the difference from CCQE? From 2p2h? …from CC1π?

$$E_{av} = \sum_{i=p,\pi^{\pm}} T_i^K + \sum_{i=\pi^0,e,\gamma} E_i$$



- Assign the difference in data and MC to various interaction modes
  - External data-driven MC correction to interaction model
- Investigate the effect of such corrections on oscillation parameters and how it may bias E_ν reconstruction

Tuning NEUT single pion model

- Short example of how tuning NEUT 5.3.3 works in NUSIANCE
  - Showing for demonstrative purposes only
- Chose ANL and BNL data without W cut, corrected[1] $\sigma(E_\nu)$ and fitting $N(Q^2)$ shape only, leading to the test statistic

$$\chi^2 = \sum^{N(\vec{x})} \left\{ 2 \sum_{i=1}^{N_{\text{bins}}} \left(\text{NEUT}_i - \text{Data}_i + \text{Data}_i \ln \left(\frac{\text{Data}_i}{\text{NEUT}_i} \right) \right) \right\} + \sum^{\sigma(E_\nu)} \left\{ \sum_{i=1}^{N_{\text{bins}}} \frac{(\text{Data}_i - \text{NEUT}_i)^2}{\delta_i^2} \right\}$$

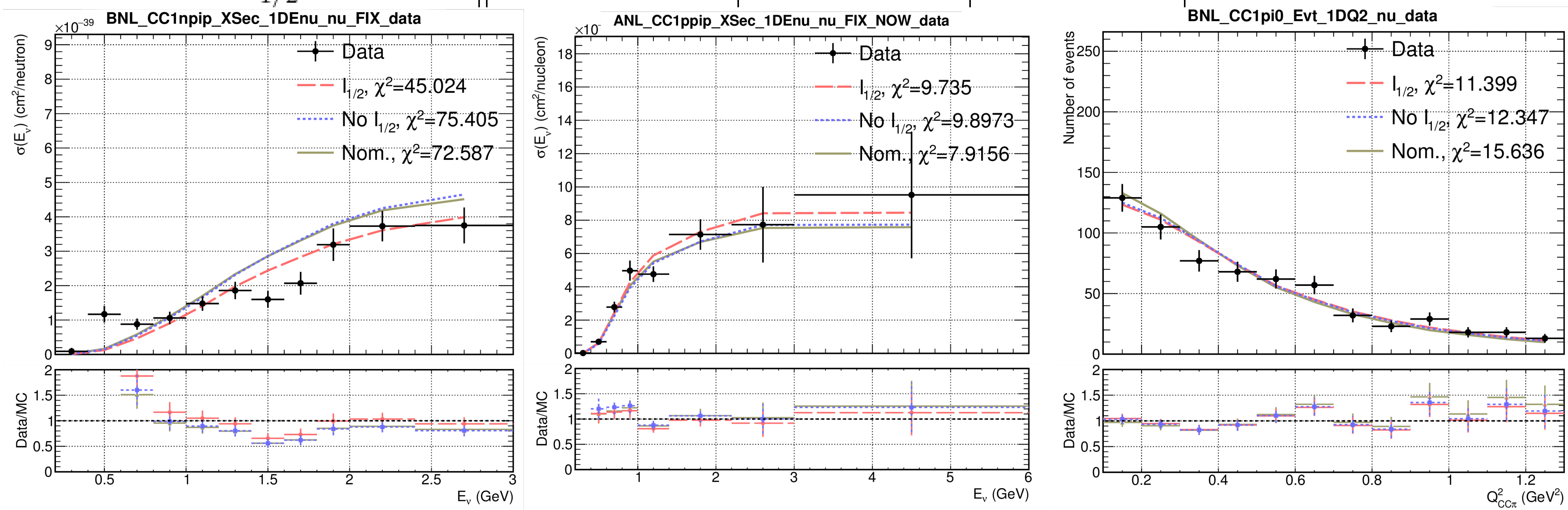
- NEUT single pion model is currently Rein-Sehgal with lepton mass effects (Kuzmin et al[2], Berger Sehgal[3]) and form factors from Graczyk & Sobczyk[4]
  - Identified three parameters: $\mathbf{M_A^{RES}}$, $\mathbf{C^A_5(0)}$ and the scaling factor for the Rein-Sehgal I½ non-resonant background, **I½ bkg**
- NUISANCE set-up in backups

[1]Phys. Dev. D90 (2014)
[2]Nucl. Phys. B Proc Supp. 139 (2005)
[3]Phys. Rev. D76 (2007)
[4]Phys. Rev. D77 (2008)

Tuning NEUT single pion model

- Non-resonant I½ background helps in many distributions, shifts $C^A_5(0)$

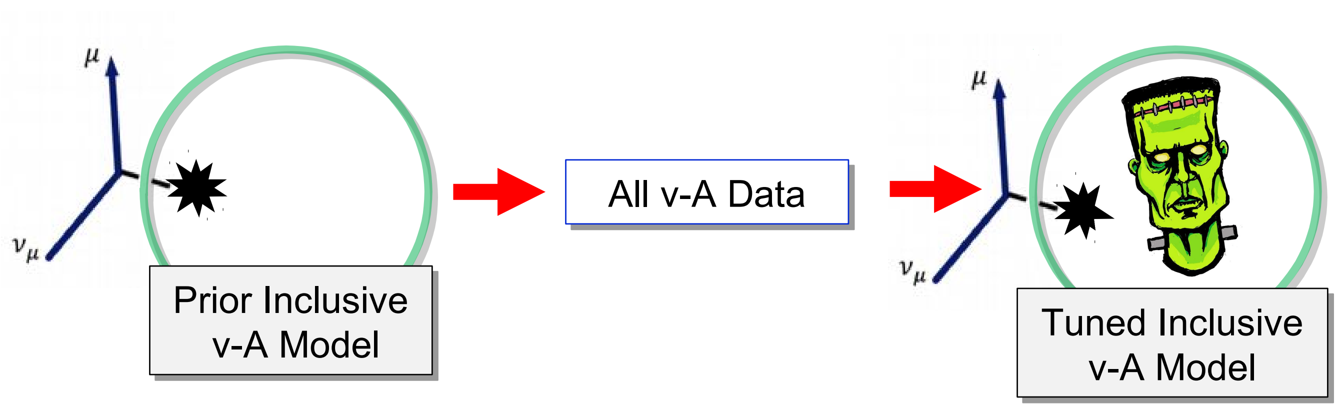
Data	M_A^{RES} (GeV)	$C_5^A(0)$	$I_{1/2}$ scale	χ^2/ndof
ANL, BNL $W < 2.0$ with $I_{1/2}$	1.07 ± 0.05	0.95 ± 0.05	0.97 ± 0.07	$235.0/137 = 1.71$
ANL, BNL $W < 2.0$ without $I_{1/2}$	1.06 ± 0.04	0.89 ± 0.06	N/A	$265.7/138 = 1.93$



- Do further analysis of parameters: other bubble chamber distributions
  - Use parameters to predict e.g. MiniBooNE CC1π⁺, CC-inclusive...

Long-term fit goal

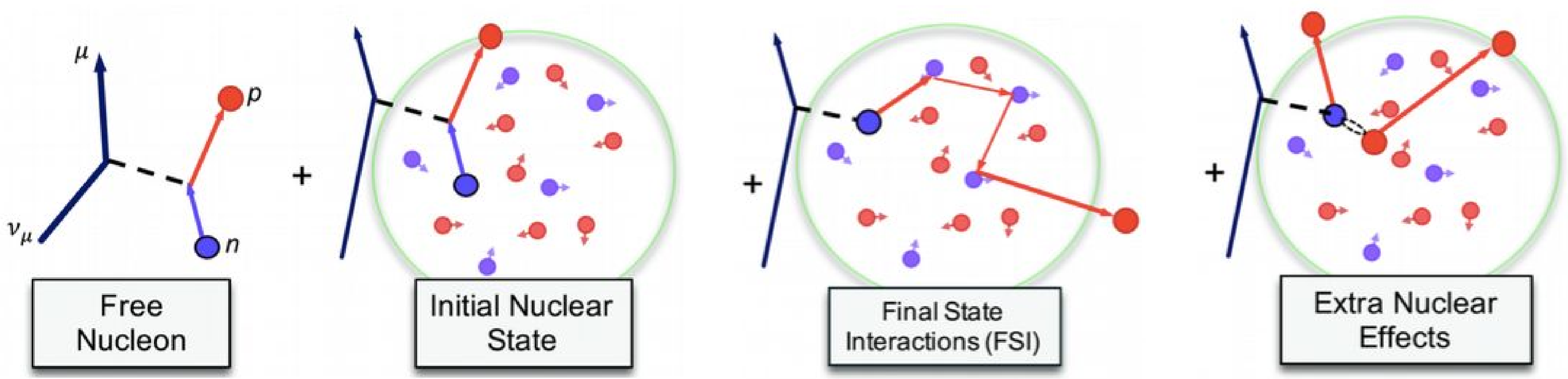
- Large ensemble of data available in NUISANCE
- Blindly fitting all parameters tells us little about physics
  - Very likely to end up with a unphysical Frankenmodel, e.g. unnaturally high M_A^{QE}, $C_A^5(0)$ far from ~1.2…
  - Not necessarily statistically correct because of missing covariances, leading to a poor test-statistic, pulls from certain experiments



- Instead develop a step-by-step tune using priors from earlier NUISANCE fits with generator experts

Long-term fit goal

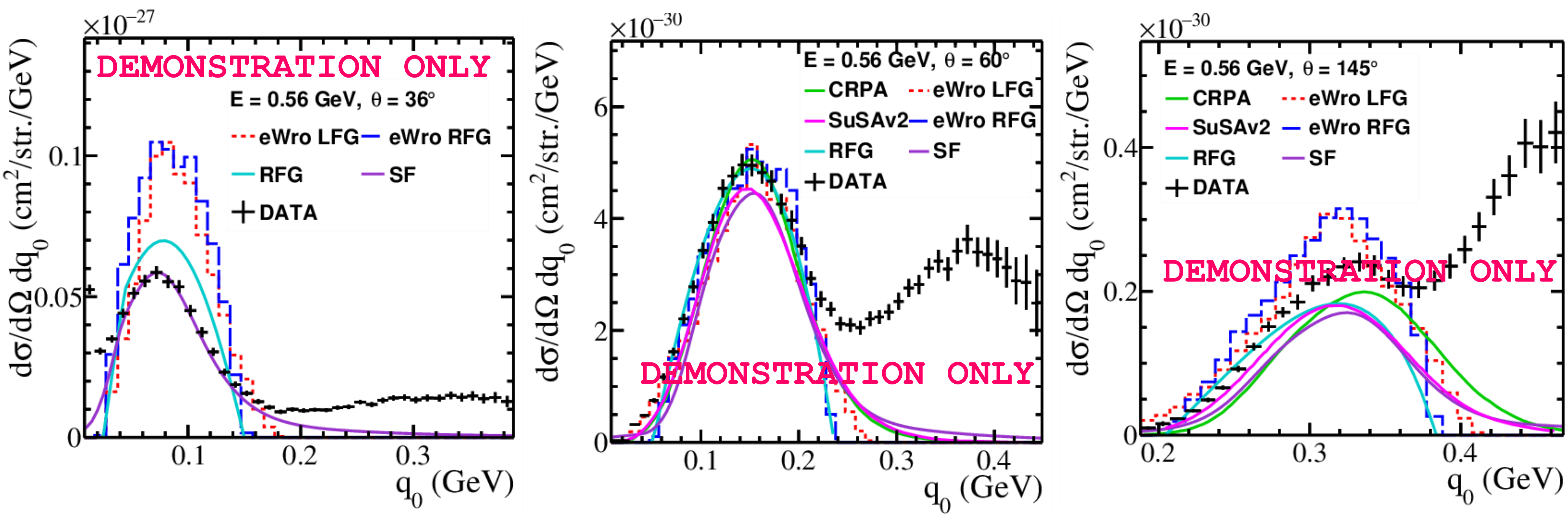
- First fit to exclusive bubble chamber data
  - Constrain the fundamental interaction without nuclear effects
- Include exclusive data from nuclear target (e.g. CC0π, CC1π^{+})
  - Use priors from BC fit, include the relevant nuclear parameters
- Include inclusive data from nuclear targets (e.g. E_{avail})
  - Use priors from earlier fit(s)



- All whilst checking for dataset compatibilities and possible tensions

Electron scattering

- **Vishvas Pandey** has joined us with expertise on electron scattering
- <u>VERY</u> preliminary, but framework is running
  - Need to validate eWro calculations
  - GENIE and GiBUU interface being built and tested
- Don't read into these, <u>showing for future plans</u>



- Special thanks to eWro group for providing <u>beta</u> version for testing

Future projects

- Attempt combined generator fits and comparisons
  - Requires the knowledge of generator experts
  - Starting with bubble chamber tunes this summer
- Patrick is working with MINERvA to develop a MINERvA tune
- Extending interface to pion and photon scattering
- Easily accessible website
  - Publish nominal predictions of generator A, B, C with models X, Y, Z
- Agree on “HepMC”-like format to include theory predictions
  - Produce outgoing particles by accept-reject
  - Make these stacks into a common format

Summary

- NUISANCE is a large open source neutrino cross-section comparison framework
- Supports simple Data/MC comparisons, systematics evaluations parameter fitting
- NEUT, GENIE, NuWro and GiBUU support
  - Additionally links to reweighting libraries
- Can inform the users of model "goodness" vs data and other generators, previous measurements, error coverage
- We encourage any collaboration; from theory and experiment

- Stay tuned for NuSTEC 2017 tutorial!

Thank you

https://nuisance.hepforge.org/

P. Stowell et al 2017 JINST 12 P01016

NUISANCE card file for 1pi tune

Parameter name in ReWeight

Specify the parameter type

Parameter start point, limits, step size, type

Sample type

```
# The NEUT parameters we're fitting
neut_parameter MaNFFRES 0.0 -5.0 5.0 1.0 FREE
neut_parameter CA5RES   0.0 -5.0 5.0 1.0 FREE
neut_parameter BgSclRES 0.0 -5.0 5.0 1.0 FREE

# Add the no W cut ANL and BNL samples
sample ANL_CC1ppip_XSec_1DEnu_nu  NEUT:@NEUT_DIR/ANL_numu_533Aut_merge.root SHAPE/NOW
sample ANL_CC1ppip_Evt_1DQ2_nu    NEUT:@NEUT_DIR/ANL_numu_533Aut_merge.root NOW

sample ANL_CC1npip_XSec_1DEnu_nu  NEUT:@NEUT_DIR/ANL_numu_533Aut_merge.root SHAPE/NOW
sample ANL_CC1npip_Evt_1DQ2_nu    NEUT:@NEUT_DIR/ANL_numu_533Aut_merge.root NOW

sample ANL_CC1pi0_XSec_1DEnu_nu   NEUT:@NEUT_DIR/ANL_numu_533Aut_merge.root SHAPE/NOW
sample ANL_CC1pi0_Evt_1DQ2_nu     NEUT:@NEUT_DIR/ANL_numu_533Aut_merge.root NOW

sample BNL_CC1ppip_XSec_1DEnu_nu  NEUT:@NEUT_DIR/BNL_numu_533Aut_merge.root SHAPE
sample BNL_CC1ppip_Evt_1DQ2_nu    NEUT:@NEUT_DIR/BNL_numu_533Aut_merge.root

sample BNL_CC1npip_XSec_1DEnu_nu  NEUT:@NEUT_DIR/BNL_numu_533Aut_merge.root SHAPE
sample BNL_CC1npip_Evt_1DQ2_nu    NEUT:@NEUT_DIR/BNL_numu_533Aut_merge.root

sample BNL_CC1pi0_XSec_1DEnu_nu   NEUT:@NEUT_DIR/BNL_numu_533Aut_merge.root SHAPE
sample BNL_CC1pi0_Evt_1DQ2_nu     NEUT:@NEUT_DIR/BNL_numu_533Aut_merge.root
```

```
./nuiscomp -c a.card -o o.root
```

Specify the data sets

File location

Specify the generator

Want to do it with GENIE instead?
Give `genie_parameter` and `GENIE:GENIE_FILE_LOCATION`

Implementing a new sample

- To implement a new sample we need
  - The data distribution (e.g. $d\sigma/dp_\mu$)
  - Method to construct a test-statistic (e.g. covariance matrix)
  - Neutrino flux distribution to generate events
  - Well-defined dependent variable (e.g. p_μ)
  - Well-defined signal definition (e.g. one $\mu^\pm$, no mesons, any nucleons)
- Measurements inherit from a `MeasurementBase` base class
- Measurements are entirely separated from the generators
  - Implement measurement once, then can use all the generators
  - All functionality enabled: compare, fit, make error bands
  - Does not require generator experts to create, modify or use measurements

Lessons from handling neutrino data

- Have handled a lot of neutrino data with varying degrees of success

- Publish and test your final **<u>covariance matrices</u>**
  - Statisticians consider **<u>data without covariances to be incomplete</u>**
  - Bob Cousins, Louis Lyons (CMS), Pumplin, Stump (CTEQ/CT10) **<u>recommended simply excluding these "useless measurements"</u>**
  - If you want maximum juice from your measurement, consider **<u>distribution-to-distribution correlations</u>**

- Signal definition needs to be reproducible in raw MC (truth)
- Don't correct for blind detector regions. **Data is pure, data is sacred**

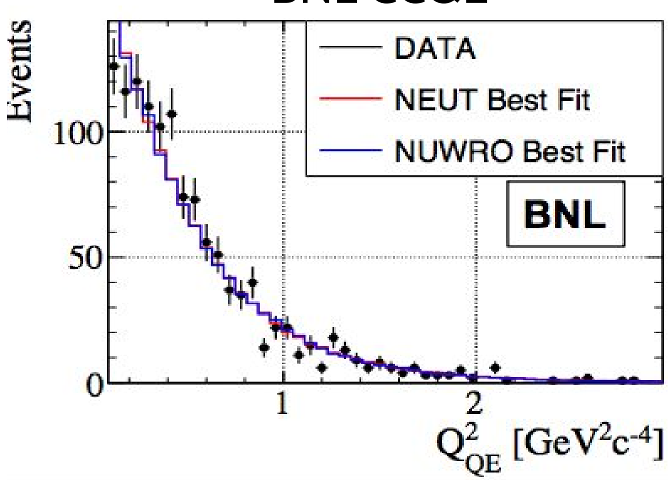
Fitting with NuWro ReWeight

- Luke and Patrick developed NuWro ReWeight for CCQE and SPP interactions; **here for demonstrative purposes**

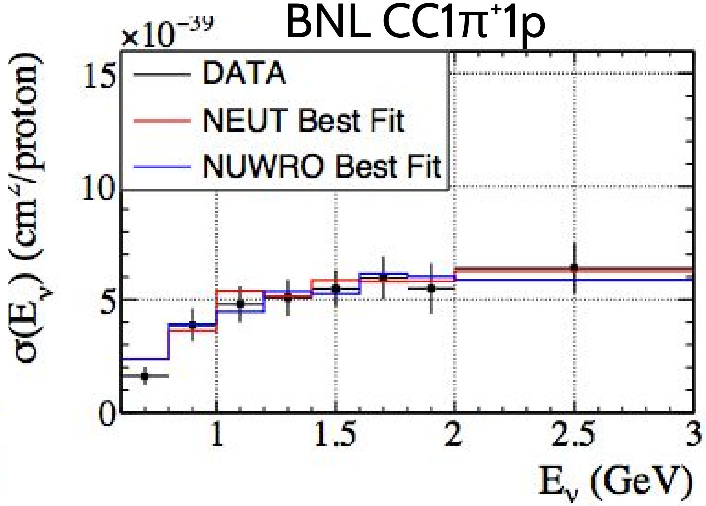
- Similar models to NEUT for free nucleon CCQE and SPP in the W < 1.4 GeV regime: expect similar results for the two generators

	QE		RES		
Fit Results	M_A [GeV/c^2]	χ^2/NDOF	M_A^{RES} [GeV/c^2]	C_A^5	χ^2/NDOF
NEUT (v5.3.6)	1.04 ± 0.03	159.8 / 146	0.89 ± 0.04	1.02 ± 0.05	102.8 / 102
NuWro (v12)	1.03 ± 0.03	154.4 / 146	0.92 ± 0.03	1.04 ± 0.05	111.9 / 102

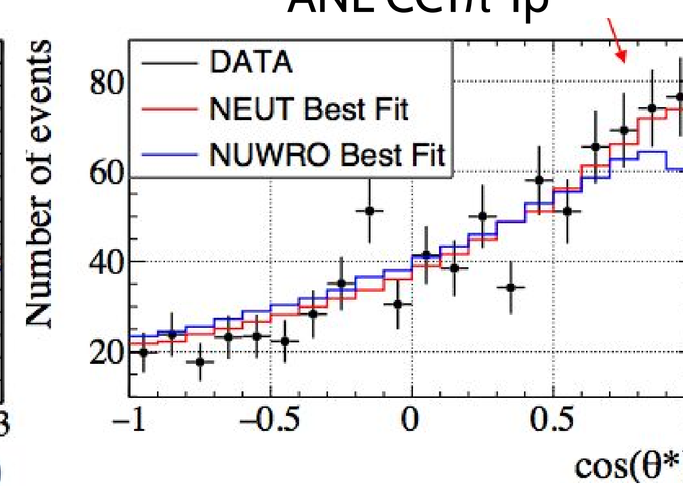
BNL CCQE



BNL CC1π⁺1p



ANL CC1π⁺1p



NEUT 5.3.6 results

- NEUT 5.3.3 result disagrees with NuWro tune
- Expected because NEUT 5.3.3 → 5.3.6 slightly different 1pi treatment
- Fitting NEUT 5.3.6 is very similar results to NuWro W < 1.4

ANL, BNL $W < 2.0$ with $I_{1/2}$	0.96 ± 0.03	1.05 ± 0.05	0.99 ± 0.07	$233.1/137 = 1.70$
NEUT 5.3.3	1.07 ± 0.05	0.95 ± 0.05	0.97 ± 0.07	$235.0/137 = 1.71$
ANL, BNL $W < 2.0$ without $I_{1/2}$	0.94 ± 0.03	1.00 ± 0.04	N/A	$256.0/138 = 1.86$
NEUT 5.3.3	1.06 ± 0.04	0.89 ± 0.06	N/A	$265.7/138 = 1.93$